7. A method of position-finding according to any previous claim in which signal processing techniques are used to produce a time-averaged value for the phase shift between signals received by the body.

8. Apparatus for position-finding for moving bodies comprising means carried by the body to receive at least three high-frequency pulse signals, the signals having substantially constant amplitudes and phase relationship and being each transmitted from a separate location, and means for deriving the body position based on the phase shift between the received signals.

9. Apparatus according to claim 8 further comprising a control station remote from the body having means for monitoring the sources of the transmitted pulse signals, means for receiving values of the phase shift between pulse signals received at the body and the said means for deriving the body position, the body having means for transmitting the said phase shift values to the control station.

10. Apparatus according to claim 8 or claim 9 in which the means carried by the body to receive the high frequency pulse signals operates the U.H.F. band.

11. Apparatus according to any of claims 8 to 10 in which the means carried by the body to receive the high frequency pulse signals is tuned to receive the synchronising pulses accompanying television broadcasts.

12. Apparatus according to any of claims 8 to 11 including signal processing and filtering means arranged to generate a time averaged value of the phase shift between the received high frequency pulse signals.

13. A method of position-finding substantially as hereinbefore described.

14. Apparatus for position-finding substantially as hereinbefore described with reference to the accompanying drawing.

Published 1990 at The Patent Office, State House, 66/71 High Holborn, London WC1R 4TP. Further copies may be obtained from The Patent Office. Sales Branch, St Mary Cray, Orpington, Kent BR5 3RD. Printed by Multiplex techniques ltd, St Mary Cray, Kent, Con. 1/87

(12) UK Patent Application (19) GB (11) 2 254 508 (13) A

(43) Date of A publication 07.10.1992

(21) Application No 9106842.9

(22) Date of filing 02.04.1991

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(51) INT CL[5]
G01S 1/24

(52) UK CL (Edition K)
H4D DPDD D268 D568 D58X
U1S S1820 S2147

(56) Documents cited
GB 2222922 A GB 2013062 A US 4555707 A

(58) Field of search
UK CL (Edition K) H4D DPDA DPDD DPDX
INT CL[5] G01S
On-line databases: WPI

(54) Vehicle location determining system

(57) The location of a vehicle or person, G5 is determined by measuring the differences in time of arrival between pairs of line or frame synchronising pulses received from 3 different TV signal transmitters S_1–S_3. The measurements are corrected for relative system time delays or signal synchronising alterations that may occur between pairs of relevant TV transmitter sites by using similar timing differences measured at a suitable known location G4 which is in radio contact with the vehicle. The intersection of the loci of the deduced distances from the transmitter sites establishes the mobile location to a reasonable degree of accuracy. The location is either presented as a set of positional co-ordinates or can be superimposed on an electronic map display.

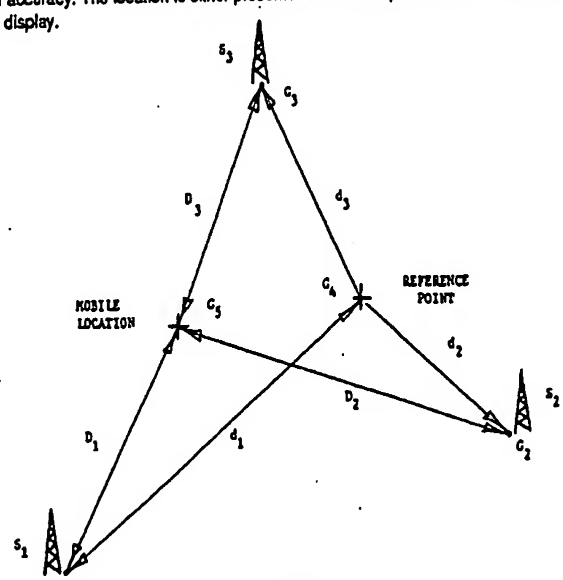

FIGURE 1

PLAN OF TV TRANSMITTER SITES & MEASUREMENT POINTS

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1/4

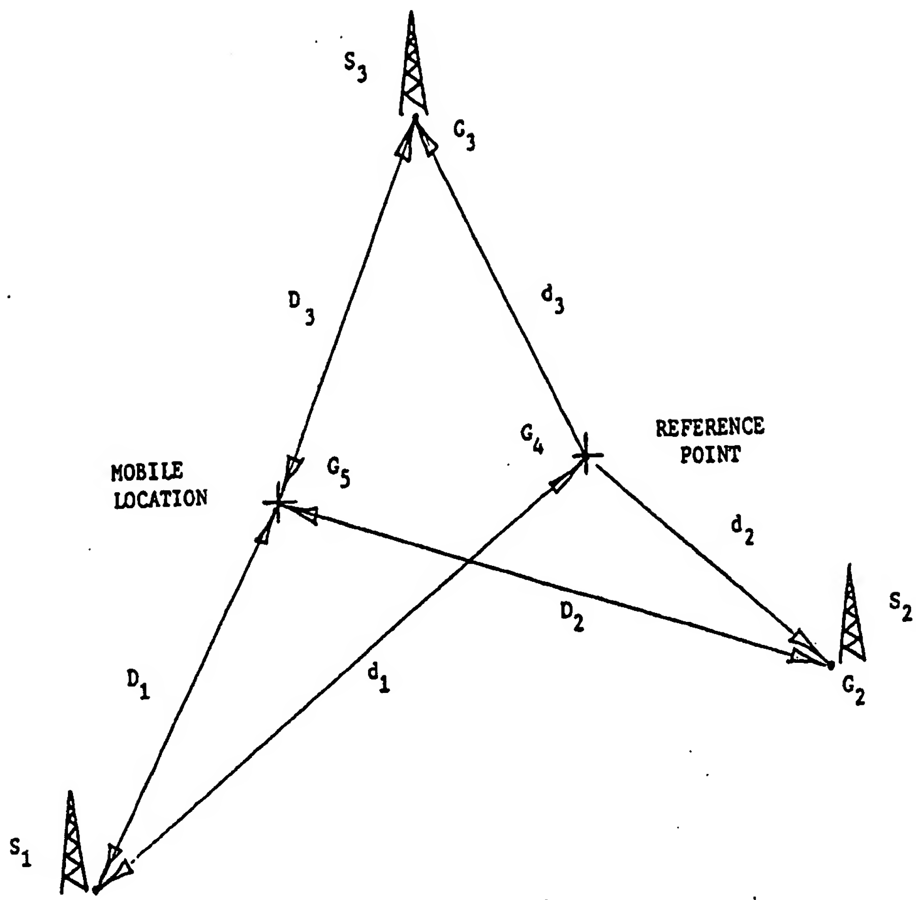
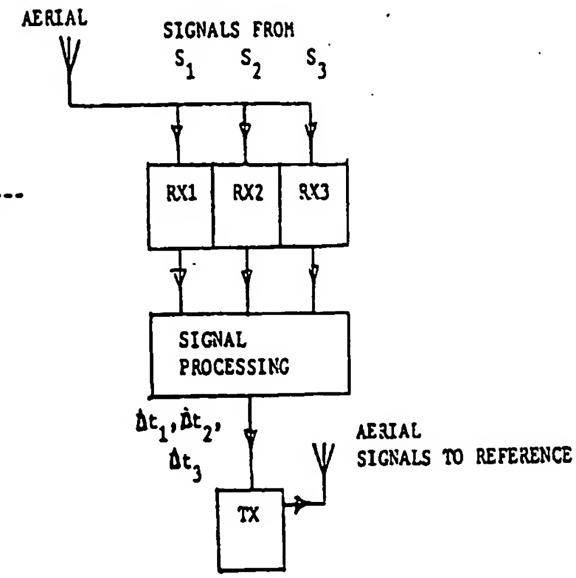


FIGURE 1

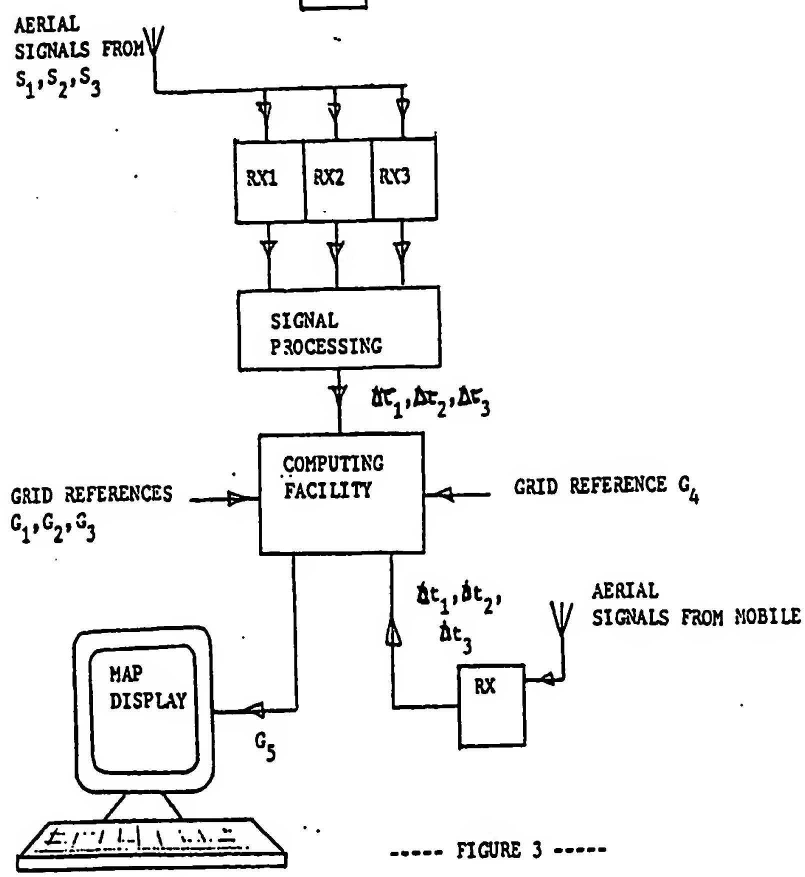
PLAN OF TV TRANSMITTER SITES & MEASUREMENT POINTS

2/4



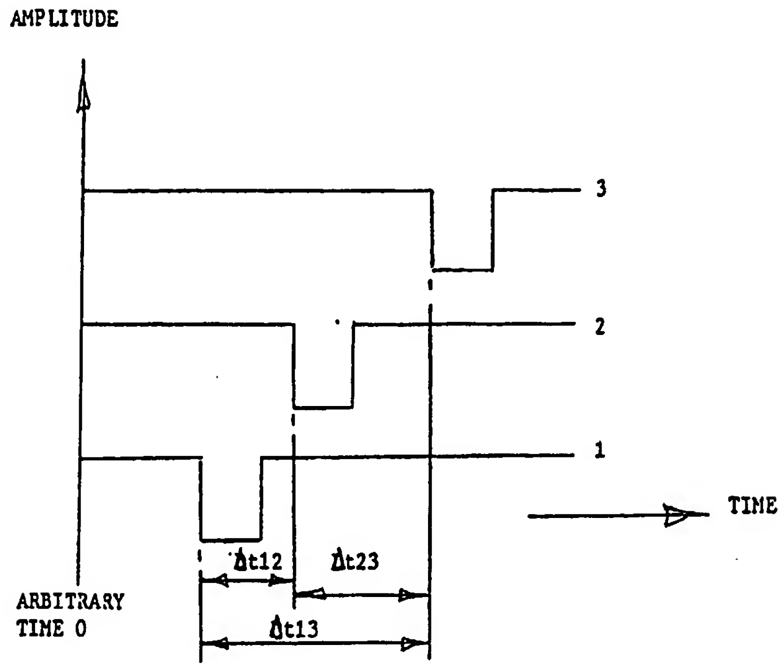
----- FIGURE 2 -----

MOBILE SYSTEM



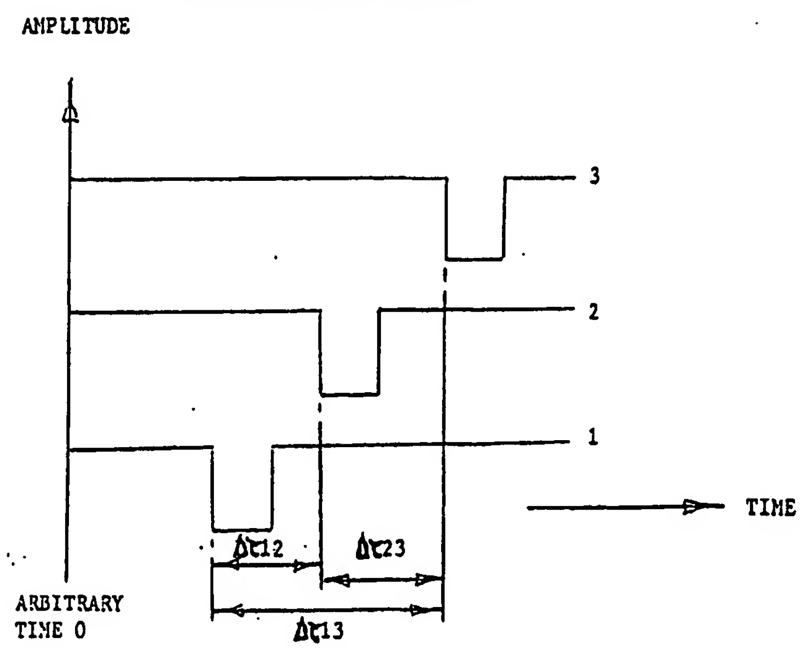
----- FIGURE 3 -----

REFERENCE SYSTEM



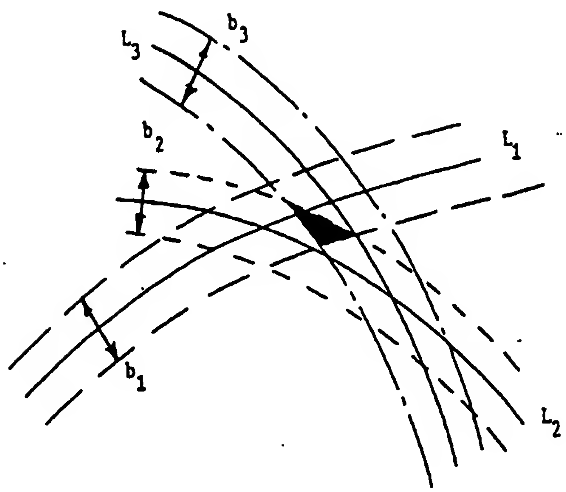
----- FIGURE 4 -----

TIMING SIGNALS AT MOBILE



----- FIGURE 5 -----

TIMING SIGNALS AT REFERENCE



----- FIGURE 6 -----

AREA OF UNCERTAINTY OF LOCATION

2254508

VEHICLE LOCATOR SYSTEM

THIS INVENTION RELATES TO AN AN AUTOMATIC ELECTRONICALLY BASED METHOD OF LOCATING VEHICLES AND OR INDIVIDUALS BY THE USE OF TV SIGNALS.

THERE IS A CONSTANT NEED TO IDENTIFY THE POSITION OF VEHICLES AND/OR INDIVIDUALS IN THE COURSE OF THEIR DAILY DEPLOYMENT. THIS IS PARTICULARLY THE CASE FOR THE EMERGENCY SERVICES, MANY GOVERNMENT AND LOCAL GOVERNMENT AGENCIES AND DEPARTMENTS AND ALSO A GREAT VARIETY OF SERVICE RELATED BUSINESSES AND ORGANISATIONS. SOME OF THE METHODS USED TO ACHEIVE THE LOCATION OF MOVING VEHICLES AND OR PERSONNEL REQUIRE EXPENSIVE AND EXTENSIVE INFRA STRUCTURE TO BE ESTABLISHED AND MAINTAINED WHICH MAKES THE COST JUSTIFICATION UNREASONABLE FOR MANY APPLICATIONS. HENCE THERE IS A LATENT DEMAND FOR AN INEXPENSIVE, RELIABLE, REPEATABLE AND ACCURATE METHOD OF MOBILE VEHICLE/PERSONNEL LOCATION. THE REQUIREMENT IS FOR A SYSTEM THAT WILL REGULARLY UPDATE THE POSITION CO-ORDINATES AND HENCE MAP THE POSITION OF VEHICLES/PERSONNEL TO PERMIT EITHER THE SUBJECT TO IDENTIFY WHERE THEY ARE OR FOR A CONTROL POINT TO BE ABLE TO REMOTELY MONITOR AND TRACK THEIR MOVEMENTS. SUCH A SYSTEM WILL HAVE GREATER APPEAL IF IT CAN BE WIDE AREA AND CAN OPERATE WITHOUT ON-GOING DEPENDANCE ON HUMAN INVOLVEMENT FOR DATA AND INFORMATION INPUT.

PRESENT INVENTION COMPRISES A SYSTEM WHICH PROVIDES THE POSITION CO-ORDINATES AND HENCE MAP REFERENCE OF A SUBJECT OVER A WIDE AREA AND WITHOUT THE NECESSITY FOR AN ON-GOING DEPENDENCE ON HUMAN INPUT. THE SYSTEM CONSISTS OF TV SIGNAL RECEIVERS LOCATED AT THE MOBILE POINT AND AT A SUITABLE REFERENCE POINT WHICH USE LOCALLY TRANSMTTED TV SIGNALS TO GENERATE TIME DIFFERENCES WHICH CAN THEN BE USED TO DETERMINE THE POSITION OF THE MOBILE. THE FRAME AND LINE SYNCHRONISING PULSES FROM OVERLAPPING TV SIGNAL TRANSMITTERS HAVE SLOW ENOUGH REPITITION RATES AND FAST ENOUGH PULSE RISE TIMES RESPECTIVELY TO PERMIT UNAMBIGUOUS AND SUFFICIENTLY ACCURATE TIME INTERVALS TO BE MEASURED BETWEEN THE SIGNALS RECEIVED FROM THE DIFFERENT TV SIGNAL TRANSMITTERS. IF 3 SEPARATE TRANSMITTER SIGNALS ARE THUS PROCESSED THEN THE 3 TIMING DIFFERENCES MEASURED AT EACH OF THE MOBILE AND REFERENCE POINTS REQUIRE TO BE MADE AVAILABLE AT A SINGLE POINT TO DETERMINE THE SUBJECTS POSITION. SINCE THERE ARE MANY AREAS IN THE UK WHERE 3 SEPARATE TV TRANSMITTERS CAN BE SIMULTANEOUSLY RECEIVED AT THE SAME LOCATION THE SYSTEM HAS WIDE AREA APPLICATION. THIS IS DONE IN THE FOLLOWING MANNER:

1. THE POSITION CO-ORDINATES OF THE TV TRANSMITTER SITES AND THE REFERENCE POINT ARE ESTABLISHED AND USED TO CALCULATE THE DISTANCE BETWEEN EACH TRANSMITTER SITE AND THE REFERENCE POINT.

2. SINCE THE SPEED OF TRAVEL OF ELECTROMAGNETIC WAVE PROPOGATION IN FREE SPACE IS KNOWN THE CALCULATED DISTANCES BETWEEN THE TRANSMITTERS AND THE REFERENCE POINT ARE THEN TRANSFERRED INTO EQUIVALENT TIMES FOR THE TRANSIT OF THE SIGNALS FROM THE TRANSMITTERS TO THE REFERENCE POINT.

3. USING AN ELECTRONIC TIMING CIRCUIT THE TIME DIFFERENCES OF RECEIVING THE FRAME AND/OR LINE SYNCHRONISING PULSES FROM EACH PAIR OF TRANSMITTERS IS MEASURED AT THE REFERENCE POINT.

4. THE DIFFERENCES BETWEEN THE RESPECTIVE VALUES OF CALCULATED TRANSMIT TIMES FROM 2 ABOVE ARE SUBTRACTED FROM THE MEASURED TIMING DIFFERENCES OBTAINED BY 3 ABOVE. THIS ESTABLISHES A TIMING CORRECTION FACTOR FOR EACH PAIR OF TRANSMITTER SIGNALS WHICH ALLOWS FOR DIFFERENCES IN RELATIVE SYSTEM DELAYS AT EACH TRANSMITTER PAIR OR SYNCHRONISING ALTERATIONS THAT MAY OCCUR BETWEEN THEM.

5. USING AN ELECTRONIC TIMING CIRCUIT THE TIME DIFFERENCES OF RECEIVING THE FRAME AND/OR LINE SYNCHRONISING PULSES FROM EACH PAIR OF TRANSMITTERS ARE MEASURED AT THE MOBILE VEHICLE/PERSONNEL POINT.

6. THE TIMING CORRECTION FACTOR AS PER 4 ABOVE AND THE TIMING DIFFERENCES AS PER 5 ABOVE ARE MADE AVAILABLE FOR FURTHER PROCESSING AT A COMMON POINT, WHICH IS MOST LIKELY THE REFERENCE POINT, BY THE USE OF A PRIVATE MOBILE RADIO (PMR) LINK OR BY SOME OTHER MEANS OF COMMUNICATION BETWEEN THE MOBILE AND THE REFERENCE POINTS.

7. THE RESPECTIVE TIMING CORRECTION FACTORS AS ESTABLISHED BY 4 ABOVE ARE APPLIED TO THE TIME DIFFERENCE VALUES OBTAINED BY 5 ABOVE.

8. THE RESULTANT TIME DIFFERENCES FROM 7 ABOVE ARE THEN TRANSORMED INTO PHYSICAL DISTANCES USING AS A CONVERSION FACTOR THE SPEED OF ELECTROMAGNETIC RADIATION PROPOGATION IN FREE SPACE WHICH IS KNOWN.

9. BY PROCESSING SIGNALS FROM 3 TRANSMITTERS AS PER THE STEPS ABOVE THERE ARE NOW 3 VALUES KNOWN FOR THE RELATIVE DISTANCES FROM THE MOBILE POINT TO EACH OF THE TRANSMITTER LOCATIONS. EITHER BY CALCULATION OR BY THE USE OF LOOK-UP TABLES THESE 3 VALUES GIVE THE MOBILE POSITION WITH RESPECT TO THE TRANSMITTER LOCATIONS WHICH ARE FIXED AND KNOWN. HENCE THE LOCATION OF THE MOBILE IS ESTABLISHED.

IT SHOULD BE NOTED THAT IF LOSS OF SIGNAL(S) OCCURS AT THE REFERENCE OR MOBILE POINT THEN THE ON GOING DETERMINATION OF THE MOBILE LOCATION CANNOT PROCEED. HOWEVER, AS SOON AS THE SIGNAL RECEPTION IS RETURNED THE FULL ACCURACY OF THE SYSTEM IS ONCE AGAIN AVAILABLE, I.E. THE MEASUREMENT SYSTEM IS NOT DEPENDANT ON EITHER KNOWING THE CO-ORDINATES OF THE STARTING POSITION OF THE MOBILE OR HAVING TO MAINTAIN CONTINUOS RECEPTION OF THE TV SIGNALS THEREAFTER. A SPECIFIC EMOBODIMENT OF THE INVENTION WILL NOW BE DISCRIBED BY WAY OF AN EXAMPLE WITH REFERENCE TO THE ACCOMPANYING FIGURES AND DRAWINGS:

FIGURE 1 SHOWS A SCHEMATIC PLAN VIEW OF 3 TV TRANSMITTER SITES. THE LOCATION OF A MOBILE SUBJECT AND A FIXED REFERENCE POINT.

FIGURE 2 SHOWS THE ELEMENTS OF A SIGNAL RECEIVER AND PROCESSOR SYSTEM FOR USE BY A MOBILE SUBJECT.

FIGURE 3. SHOWS THE ELEMENTS OF A SIGNAL RECEIVER AND PROCESSOR SYSTEM FOR USE AT A FIXED REFERENCE POINT.

FIGURE 4 SHOWS THE SIGNAL TIMING DIFFERENCES MEASURED AT A MOBILE VEHICLE/PERSON.

FIGURE 5 SHOWS THE SIGNAL TIMING DIFFERENCES MEASURED AT A FIXED REFERENCE POINT.

FIGURE 6 SHOWS A TYPICAL AREA OF UNCERTAINTY OF POSITION ESTABLISHMENT FOR A MOBILE VEHICLE/PERSON.

WITH REFERENCE TO THE ABOVE FIGURES THE VEHICLE LOCATION SYSTEM OPERATES AS FOLLOWS.

THERE ARE 3 TV TRANSMITTER SITES S1, S2 AND S3 WITH KNOWN GRID REFERENCES OF G1,G2 AND G3 RESPECTIVELY. A FIXED REFERENCE POINT WITHIN THE RECEPTION AREA AT THE TRANSMITTERS S1, S2 AND S3 HAS A KNOWN GRID REFERENCE OF G4 AND IS LOCATED A DISTANCE d1, d2 AND d3 FROM S1, S2 AND S3 RESPECTIVELY. A MOBILE VEHICLE/PERSON IS WITHIN THE RECEPTION AREA OF THE TRANSMITTERS AT S1, S2 AND S3 AND HAS AN UNKNOWN GRID REFERENCE G5. THE MOBILE POINT IS LOCATED AT A DISTANCE OF D1, D2 AND D3 FROM TRANSMITTER SITES S1. S2 AND S3 RESPECTIVELY.

WITH REFERENCE TO FIGURE 2 THE TV SIGNALS TRANSMITTED FROM THE SITES S1, S2 AND S3 ARE RECEIVED BY TUNED RECEIVERS RX1, RX2 AND RX3 RESPECTIVELY LOCATED AT THE MOBILE POINT. THE LINE SYNCHRONISING SIGNALS RECEIVED FROM EACH OF THE TRANSMITTERS ARE COMPARED ON A TIME BASE AS SHOWN IN FIGURE 4. THE TIME DIFFERENCES OF THE SIGNALS FROM TRANSMITTERS 1 & 2, 2 & 3 AND 1 & 3 ARE ELECTRONICALLY TIMED AS $\Delta t12$, $\Delta t23$ amd $\Delta t13$ RESPECTIVELY.

WITH REFERENCE TO FIGURE 3 THE TV SIGNALS TRANSMITTED FROM THE SITES S1, S2 AND S3 ARE RECEIVED BY TUNED RECEIVERS RX1, RX2 AND RX3 RESPECTIVELY LOCATED AT THE REFERENCE POINT. THE LINE SYNCHRONISING SIGNALS RECEIVED FROM EACH OF THE TRANSMITTERS ARE COMPARED ON A TIME BASE AS SHOWN IN FIGURE 5. THE TIME DIFFERENCES OF THE SIGNALS FROM TRANSMITTERS 1 & 2, 2 & 3 AND 1 & 3 ARE ELECTRONICALLY TIMED AS $\Delta\tau_{12}$, $\Delta\tau_{23}$ AND $\Delta\tau_{13}$ RESPECTIVELY.

WITH FURTHER REFERENCE TO FIGURE 3 A COMPUTING FACILITY IS AVAILABLE AT THE REFERENCE POINT WHICH HAS THE FOLLOWING DATA AS INPUT.

1. THE VALUES OF $\Delta\tau_{12}$, $\Delta\tau_{23}$ AND $\Delta\tau_{13}$.

2. THE VALUES OF Δt_{12}, Δt_{23} AND Δt_{13} WHICH ARE OBTAINED AT THE REFERENCE POINT FROM THE MOBILE LOCATION ACROSS A PRIVATE MOBILE RADIO (PMR) LINK.

3. GRID REFERENCES G1, G2, G3 AND G4.

THE COMPUTING FACILITY USES THE GRID REFERENCES G1, G2, G3 AND G4 TO CALCULATE DIFFERENCES IN DISTANCE BETWEEN THE REFERENCE POINT AND EACH PAIR OF TRANSMITTERS SHOWN IN FIGURE 1. J.E. (d1 - d2), (d2 - d3) AND (d1 - d3). IF ΔT1, ΔT2 AND ΔT3 ARE THE TIMES FOR ELECTROMAGNETIC RADIATION IN FREE SPACE TO TRAVEL THE DISTANCES (d1 - d2)), (d2 - d3) AND (d1 - d3) RESPECTIVELY THEN THE MOBILE VEHICLE/PERSON IS A DISTANCE (D1 - D2), (D2 - D3) AND (D1 - D3) RESPECTIVELY NEARER TO S1, S2 AND S3 RESPECTIVELY THAN S2, S3 AND S3 RESPECTIVELY. FURTHERMORE THESE 3 DISTANCES CAN BE CALCULATED BY THE FOLLOWING RELATIONSHIPS:

$$(D1 - D2) = K.\Delta T12 \quad - \quad (1)$$

$$(D2 - D3) = K.\Delta T23 \quad - \quad (2)$$

$$(D1 - D3) = K.\Delta T13 \quad - \quad (3)$$

WHERE K = SPEED OF ELECTROMAGNETIC RADIATION IN FREE SPACE

AND

$$\Delta T12 = \Delta t12 - (\Delta\tau 12 - \Delta T1)$$

$$\Delta T23 = \Delta t23 - (\Delta\tau 23 - \Delta T2)$$

$$\Delta T13 = \Delta t13 - (\Delta\tau 13 - \Delta T3)$$

FIGURE 6 SHOWS THE LOCUS PLOTS L1, L2 AND L3 WHICH ARE LINES OF CONSTANT VALUES OF THE DISTANCES (D1 - D2), (D2 - D3) AND (D1 - D3) RESPECTIVELY. GIVEN THAT THERE ARE FINITE RESOLUTIONS OF MEASUREMENT OF THE Δt AND $\Delta\tau$ VALUES THEN THE LOCUS PLOTS L1, L2 AND L3 MAY NOT BE COINCIDENTAL.

HOWEVER IF THE LOCUS PLOTS L1, L2 AND L3 ARE KNOWN TO BE ACCURATE TO WITHIN THE RANGE OF b1, b2 AND b3 RESPECTIVELY THEN THE POSITION OF THE MOBILE VEHICLE/PERSON MUST BE WITHIN THE SHADED AREA WHICH IS THE AREA WITHIN WHICH ALL POINTS ARE WITHIN THE CALCULATED LEVEL OF ACCURACY OF EACH INDIVIDUAL LOCUS PLOT I.E. $L1 \pm \frac{b1}{2}$, $L2 \pm \frac{b2}{2}$ AND $L3 \pm \frac{b3}{2}$. BY THE METHOD OF LEAST SQUARES APPROXIMATION OR BY AN ALTERNATIVE ACCEPTED MEANS OF ARITHMETIC AVERAGING THE POSITION OF THE MOBILE VEHICLE/PERSON WITH RESPECT TO S1, S2 AND S3 IS ESTABLISHED. SINCE THE POSITION CO-ORDINATES OF S1, S2 AND S3 ARE KNOWN THEN THE ASSOCIATE POSITION CO-ORDINATES OF THE MOBILE POINT CAN BE CALCULATED. THESE CO-ORDINATES CAN THEN BE USED TO SHOW ON A VISUAL DISPLAY UNIT A MAP POSITION AS SHOWN IN FIGURE 3.

IF REQUIRED THE MOBILE REFERENCE SYSTEMS DESCRIBED IN FIGURES 2 AND 3 CAN BE MODIFIED TO CARRY OUT THE COMPTUTATIONAL OPERATIONS AT THE MOBILE (OR SOME OTHER LOCATION) RATHER THAN THE REFERENCE POINT. IN WHICH CASE VALUES FOR $\Delta\tau 12$, $\Delta\tau 23$ AND $\Delta\tau 13$ ARE TRANSMITTED FROM THE REFERENCE POINT TO THE MOBILE POINT (OR SOME OTHER LOCATION INSTEAD OF THE REVERSE AS SHOWN IN FIGURES 2 AND 3.

FURTHERMORE IF SO ARRANGED 2 RECEIVERS IN PLACE OF 3 CAN BE USED AT THE REFERENCE AND/OR MOBILE POINTS. THIS IS ACHEIVED BY FIRST MEASURING THE TIME DIFFERENCE BETWEEN SIGNALS 1 & 2 ON RECEIVERS RX1 & RX2 RESPECTIVELY RX2 IS THEN MADE TO OPERATE AS RX3. THE TIME DIFFERENCE BETWEEN SIGNALS 1 & 3 IS THEN MEASURED. RX1 IS THEN MADE TO OPERATE AS RX2 AND THE TIME DIFFERENCE BETWEEN SIGNALS 2 & 3 IS MEASURED. THESE SWITCHING OPERATIONS MAY BE CARRIED OUT MANUALLY OR ELECTRONICALLY.

DEPENDING ON THE POSITION OF THE CHOSEN REFERENCE POINT AND THE POSITION OF THE MOBILE THE PARTICULAR COMBINATION OF SITES S1, S2 AND S3 MAY REQUIRE TO BE CHANGED IN ORDER TO HAVE 3 TRANSMITTING SITES WHICH CAN BE RECEIVED AT REFERENCE AND MOBILE POINTS HAVING GRID REFERENCES G4 AND G5 RESPECTIVELY. THE OPERATION TO PERMIT TWO SETS OF RECEIVERS RX1, RX2 AND RX3 TO RECEIVE A DIFFERENT COMBINATION OF SITES MAY BE CARRIED OUT MANUALLY OR ELECTRONICALLY. IT SHOULD ALSO BE NOTED THAT THE FRAME SYNCHRONISING SIGNAL REPETITION RATE IS 25 TIMES/SECOND OR EVERY 40 mSECS WHICH AT THE SPEED OF ELECTROMAGNETIC RADIATION PROPOGATION IN FREE SPACE REPRESENTS A DISTANCE OF SOME 13.000 KILOMETRES. HENCE THERE IS NO AMBIGUITY AT THE REFERENCE AND MOBILE MEASUREMENT POINTS AS TO WHICH FRAME PERIOD IS BEING USED TO DEDUCE THE MOBILE POSITION.

HOWEVER SINCE EACH NEW LINE SYNCHRONISING PULSE OCCURS EVERY $\frac{40}{625}$ mSECS THIS CORRESPONDS TO A DISTANCE OF FREE SPACE ELECTROMAGNETIC PROPAGATION OF APPROXIMATELY 20 KILOMETRES HENCE IT NEEDS TO BE NOTED WHICH LINE SYNCHRONISING PULSE IS BEING USED FOR THE TIMING OPERATIONS AT THE REFERENCE AND MOBILE MEASUREMENT POINTS SINCE THE AREA OF OPERATIONAL COVERAGE OF A PARTICULAR COMBINATION OF TV BASE SITES S1, S2 AND S3 COULD OFTEN BE GREATER THAN APPROXIMATELY 20 KILOMETRES SQUARE.

REGARDING TOPOGRAPHICAL CHANGES, IT IS RECOGNISED THAT THE SITES S1, S2 AND S3 WILL NORMALLY BE LOCATED AT HEIGHTS CONSIDERABLY HIGHER ABOVE MEAN SEA LEVEL THAN MOST IF NOT ALL OF THE EFFECTIVE OPERATIONAL AREA OF THE MOBILE AND THE LOCATION OF THE REFERENCE POINT, EITHER BY CALCULATION OR BY USING SUITABLE MODIFICATIONS OF THE LOOK-UP TABLES LOCATED IN THE COMPUTING FACILITY THESE HEIGHT DIFFERENCES CAN BE TAKEN INTO CONSIDERATION IN ORDER TO MINIMISE ERRORS INTRODUCED BY ALL POINTS NOT BEING AT THE SAME HEIGHT ABOVE MEAN SEA LEVEL.

FINALLY, REGARDING THE ACCURACY OF MEASUREMENT IT IS RECOGNISED THAT THIS IS LARGELY LIMITED BY THE RISE TIME OF THE LINE SYNCHRIONISING PULSE AND HENCE ITS ABILITY TO ACT AS A REPEATABLE SWITCH FOR TIMING PURPOSES. TYPICALLY THIS RISE TIME IS NO MORE THAN 0.2 μSEC WHICH REPRESENTS A DISTANCE OF APPROXIMATELY 65 M FOR THE PROPOGATION OF ELECTROMAGNETIC RADIATION IN FREE SPACE HENCE ALLOWING FOR THIS RESOLUTION IN TIMING MEASUREMENTS AND ALSO THE ERRORS INTRODUCED FROM THE COMPUTATIONAL STEPS TO BE MADE, THE OVERALL ACCURACY OF THE SYSTEM GIVES A POSITIONAL REFERENCE FOR THE MOBILE POINT TO WITHIN AN ABSOLUTE ACCURACY OF A FEW HUNDRED METRES, AT WORST THE AREA OF UNCERTAINTY OF THE MEASUREMENT AS DESCRIBED ABOVE COULD HOWEVER CONSIDERABLY IMPROVE ON THIS DEGREE OF ACCURACY.

CLAIMS

1. AN ELECTRONIC MEANS OF TV SIGNAL RECEPTION AND SIGNAL PROCESSING FROM 3 DIFFERENT TRANSMITTER SITES WHERE BY THE GRID REFERENCE OF THE LOCATION OF A VEHICLE OR PERSON WITHIN THE SIGNAL RECEPTION AREAS OF THESE SITES CAN BE CALCULATED OR DEDUCED TO A USEFUL LEVEL OF ACCURACY. THE TV LINE AND FRAME SYNCHRONISING PULSES HAVE SUITABLY FAST RISE TIMES AND SLOW REPITITION RATES RESPECTIVELY TO PERMIT THE GENERATION OF A SERIES OF UNAMBIGUOUS TIMING DIFFERENCES WHICH HAVE A SUFFICIENT DEGREE OF ACCURACY TO PERMIT RELATIVE DISTANCES TO BE CALCULATED BASED ON THE KNOWN SPEED OF ELECTROMAGNETIC WAVE PROPAGATION IN FREE SPACE.

2. A SYSTEM AS DESCRIBED IN CLAIM 1 WHICH USES A REFERENCE TV SIGNAL RECEIVING POINT WITH A KNOWN GRID REFERENCE IN ORDER TO ELIMINATE ANY RELATIVE SYSTEM TIME DELAYS OR SIGNAL SYNCHRONISING ALTERATIONS THAT MAY OCCUR BETWEEN PAIRS OF RELEVANT TV TRANSMITTER SITES.

3. A SYSTEM AS DESCRIBED IN CLAIMS 1 AND 2 WHERE THERE IS A COMPUTING FACILITY LOCATED EITHER AT THE MOBILE OR REFERENCE POINT OR AT SOME OTHER LOCATION WHICH IS USED TO AUTO-MATICALLY CALCULATE OR DEDUCE THE GRID REFERENCE OF THE MOBILE LOCATION WHICH CAN THEN BE SHOWN ON AN ELECTRONICALLY GENERATED MAP DISPLAY ON A VISUAL DISPLAY UNIT OR USED IN SOME OTHER SUITABLE FORM OF PRESENTATION.

THIS CLAIM DEPENDS ON A SUITABLE COMMUNICATIONS LINK EXISTING BETWEEN THE MOBILE AND REFERENCE POINTS OR BETWEEN BOTH THESE POINTS AND SOME OTHER 3RD POINT.

4. THE POSITIONAL ACCURACY OBTAINED BY THE SYSTEM IN CLAIMS 1.2 AND 3 CAN BE IMPROVED BY PROCESSING ALL 3 RATHER THAN 2 PAIRS OF SIGNALS FROM THE 3 RELEVANT TV TRANSMITTER SITES.

5. THE TV SIGNAL RECEPTION CIRCUITRY USED BY THE SYSTEM DESCRIBED IN CLAIMS 1 AND 2 MAY BE SIMPLIFIED BY USING 2 SWITCHABLE RECEIVERS RATHER THAN 3 PRE-TUNED RECEIVERS AT BOTH OR EITHER OF THE REFERENCE AND MOBILE MEASUREMENT POINTS.

6. INTERMITTANT RECEPTION OF TV SIGNALS RECEIVED IN THE SYSTEM DESCRIBED IN CLAIMS 1, 2 AND 3 ABOVE WILL NOT IMPAIR THE ACCURACY OF THE DEDUCED MOBILE LOCATION DURING PERIODS WHEN THE SIGNALS ARE NOT ALL RECEIVED. THIS ALSO MEANS THAT THE STARTING LOCATION OF THE MOBILE IS IRRELEVANT TO THE OPERATION OF THE SYSTEM.

7. THE ACCURACY OF THE CALCULATED OR DEDUCED LOCATION OF THE MOBILE POINT AS PER CLAIMS 1,2 AND 3 CAN BE IMPROVED ON BY MAKING APPROPRIATE CORRECTIONS FOR THE RELATIVE HEIGHTS OF THE TV SIGNAL TRANSMITTING AND RECEPTION POINTS.

8. THE SYSTEM DESCRIBED IN CLAIMS 1 AND 2 CAN GIVE VERY WIDE AREA COVERAGE OF MOBILE LOCATION BY SWITCHING THE TUNED RECEIVERS AT THE REFERENCE AND MOBILE POINTS TO RECEIVE SIGNALS FROM THE MOST SUITABLE SET OF 3 TV TRANSMITTERS AVAILABLE.

Amendments to the claims
have been filed as follows

1. A method of determining the location of a mobile body comprising receiving a television signal from three different transmitter sites, determining the difference in propagation time for signals from each pair of said three transmitter sites to arrive at said location by measuring the differences in the times of arrival at said location of frame and/or line synchronising pulses forming part of said television signal, and deriving the location of said mobile body therefrom.

2. A method as claimed in Claim 1, further including the step of correcting each of said measured time differences by a respective correction factor based upon the respective difference in propagation time for signals from each pair of said three transmitters to arrive at a known reference location.

3. A method as claimed in Claim 2, wherein a permanent receiving station is located at said reference location, said correction factors being periodically updated to take account of alterations in synchronism between the transmission of said signal from said transmitter sites.

4. A method as claimed in Claim 3, wherein said correction factors are derived by calculating the difference in propagation time for signals from each pair of said transmitter sites to arrive at said reference location, from the known distance between said reference location and each of said transmitter sites and the known speed of electromagnetic propagation, measuring the differences in the times of

arrival of said frame and/or line synchronising pulses at said reference location from each of said transmitter sites, and subtracting said calculated time differences from the respective measured time differences.

5. A method as claimed in Claim 3 or Claim 4, wherein the time differences measured at said mobile body are communicated by any suitable means to said permanent receiving station, the location of the mobile body being derived by computer means at said station.

6. A method as claimed in Claim 3 or Claim 4, wherein said time differences measured at said reference location or said correction factors are communicated by any suitable means to said mobile body, the location of the mobile body being derived by computer means carried by said mobile body.

7. A method as claimed in Claim 5 or Claim 6, wherein the location of said mobile body is expressed as a grid reference and/or displayed on suitable visual display means.

8. A method as claimed in any preceding Claim, wherein the relative heights of said transmitter site aerials are taken into account in the calculation of time differences and distances.

9. Apparatus for determining the location of a mobile body, comprising television signal receiver means adapted to receive a television signal from each of three transmitter sites, signal processing means for measuring the differences in the times of arrival between frame and/or line synchronising pulses forming

part of said television signal from each pair of said three transmitter sites, and computer means adapted to derive the location of said mobile body from said time differences.

10. Apparatus as claimed in Claim 9, wherein said computer means is further adapted to correct said time differences by the application of correction factors thereto.

11. Apparatus as claimed in Claim 10, wherein said signal receiver and signal processing means are carried by said mobile body, said apparatus further including second, similarly adapted signal receiver and signal processing means located at a known reference location and adapted to measure a second set of time differences at said reference location, said computer means being adapted to calculate said correction factors from said second set of time differences and from the known relative positions of said transmitter sites and said reference location.

12. Apparatus as claimed in Claim 11, wherein said computer means is located at said reference location, and wherein said mobile body also carries means for communicating said measured time differences from said mobile body to said reference location.

13. Apparatus as claimed in Claim 11, wherein said computer means is carried by said mobile body and means are located at said reference location for communicating said correction factors and/or said second set of time differences to said mobile body.

14. Apparatus as claimed in any one of Claims 9 to 13,

further including visual display means for displaying the location of said mobile body.

15. Apparatus as claimed in any one of Claims 9 to 14, wherein said signal receiver means includes one receiver for each of said transmitter sites.

16. Apparatus as claimed in any one of Claims 9 to 14, wherein said receiver means includes two receivers, at least one of which is adapted to receive said signal from any selected one of a plurality of transmitter sites.

17. Apparatus as claimed in any one of Claims 9 to 16, wherein said receiver means is adapted to selectively receive signals from the most appropriate three out of a larger plurality of transmitter sites.

18. A method of determining the location of a mobile body, substantially as hereinbefore described with reference to the accompanying drawings.

19. Apparatus for determining the location of a mobile body, substantially as hereinbefore described with reference to the accompanying drawings,

Indoor Geolocation using OFDM Signals in HIPERLAN/2 Wireless LANs

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ABSTRACT

With the finalization of new series of IEEE 802.11 and ETSI HIPERLAN standards, it becomes very important and interesting to study the methods to integrate geolocation functionalities into the next generation wireless LANs. In this paper we investigate geolocation methods and system architectures using OFDM signals in HIPERLAN/2 wireless LANs. We propose a novel method to measure geolocation metrics by exploiting the HIPERLAN/2 MAC frame structure. Computer simulation results are presented to show the performance of the geolocation systems using OFDM signals.

I. INTRODUCTION

Providing geolocation services and integrating context awareness is becoming one of the future trends of wireless data communication systems. As a result of FCC ruling concerning the enhanced wireless E911 services, considerable interests have been attracted to geolocation techniques. Similar to the geolocation applications in cellular systems, there are increasing needs in indoor environments (e.g. hospital, warehouse and emergency site) to locate expensive equipments or people (e.g. patients, children, firefighters, soldiers and policemen) [1][2]. These incentives have led to research in designing accurate geolocation systems in indoor environment where the severe multi-path radio propagation and lack of line-of-sight signal makes it very difficult for traditional GPS systems and cellular geolocation systems to provide adequate accuracy.

Geolocation information can be extracted either from a dedicated infrastructure and signaling system (e.g. GPS systems) or from an existing infrastructure and signaling system designed for wireless voice or data communications (e.g. providing geolocation services within existing cellular systems) [2]. Compared to the method of using dedicated systems, extracting geolocation information from existing signaling systems is more challenging. However, exploiting existing infrastructures and signaling system for geolocation purpose is more attractive because by using this method, geolocation related services can be easily integrated into existing wireless communication systems without significant changes in both mobile terminals and network infrastructures. With the finalization of new series of IEEE 802.11 and ETSI BRAN HIPERLAN standards, new features are being integrated into the next generation wireless LANs and it becomes very important and interesting to study the methods to integrate geolocation functionality into wireless LANs.

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During the past decade, geolocation methods in DSSS (Direct Sequence Spread Spectrum) systems have been well studied. The autocorrelation properties of PN sequences make DSSS systems very suitable for ranging and geolocation applications. More recently, OFDM has been adopted by ETSI HIPERLAN/2 and IEEE 802.11a as physical layer standard for next generation wireless LANs. However, no similar studies of using OFDM systems for geolocation applications have been reported in the literature. In this paper, we investigate geolocation methods and system architectures using OFDM signals in HIPERLAN/2 wireless LANs. We propose a novel method to measure geolocation metrics TOA (Time of Arrival) and TDOA (Time Difference of Arrival) by exploiting the HIPERLAN/2 MAC frame structure.

The paper is organized as follows. In Section 2, we review those aspects of HIPERLAN/2 standards that are relevant to geolocation considerations. Then in the following section, we investigate geolocation methods and architectures in HIPERLAN/2 wireless LANs. In Section 4, we present a burst synchronization method in HIPERLAN/2 OFDM systems that can be used to extract geolocation metrics from OFDM signals. In Section 5, simulation results are presented to show the performance of OFDM based geolocation systems.

II. REVIEW OF HIPERLAN/2

The HIPERLAN is a collective reference to High Performance Radio Local Area Networks standards developed or been developing by ETSI (European Telecommunications Standards Institute) project BRAN (Broadband Radio Access Networks) [4][5]. The HIPERLAN/2 network operates in 5 GHz band, and it supports short-range broadband wireless access, 30m in typical indoor environment and up to 150m in typical outdoor or large open indoor environment.

A HIPERLAN/2 network typically has a configuration as shown in Figure 1. A number of Access Points (AP), each of which covers a certain area, are connected to a core network and form together a radio access network. The mobile terminal (MT) associates with one of the APs and communicate with the associated AP over the radio channel. Handoff between APs will be performed for the roaming MTs when necessary. HIPERLAN/2 defines two basic operation modes, the mandatory

Centralized Mode and the optional Direct Mode. In the Centralized Mode, APs are connected to a core network that serves MTs associated to it. All traffic must pass through AP even if the data exchange is between two MTs in the same serving area of the AP. In the optional Direct Mode, the medium access is still controlled by a central controller but this controller needs not necessarily be connected to a core network. The MTs may communicate directly between each other. In a HIPERLAN/2 network, data transmission between MT and AP is connection-oriented. There are two types of connections, bi-directional point-to-point and unidirectional point-to-multipoint (from AP to MT). The connections between MTs and AP, which are time-division multiplexed over the air interface, are established prior to the transmission using signaling functions.

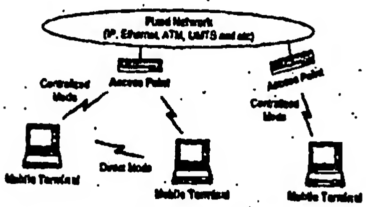

Figure 1: The HIPERLAN/2 network.

HIPERLAN/2 protocol has three basic layers: Physical (PHY) layer, Data Link Control (DLC) layer, and Convergence layer (CL). The PHY layer defines basic data transmission functions via radio channel. The DLC layer consists of Medium Access Control (MAC) function, Error Control (EC) function and Radio Link Control (RLC) function. The Convergence layer works as an intermediate component between the DLC layer and a variety of fixed networks, e.g. IP, Ethernet, ATM, UMTS and etc., to which HIPERLAN/2 network is connected.

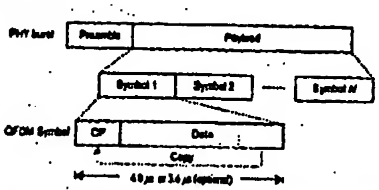

Figure 2: HIPERLAN/2 physical layer burst format with OFDM signaling.

The PHY layer of HIPERLAN/2 is based on a multicarrier modulation scheme OFDM (Orthogonal Frequency Division Multiplexing). The basic idea of the OFDM is to divide a wideband selective channel into a number of independent narrowband sub-channels so that the narrowband sub-channels can be viewed as non-selective or flat fading. OFDM can be efficiently implemented using FFT (Fast Fourier Transform) and IFFT (Inverse FFT) at the receiver and the transmitter respectively. In such a scheme, to avoid inter-symbol-interference (ISI) and to combat multipath effects, a cyclic prefix (CP), which is a copy of the ending part of OFDM symbol, is added at the beginning of each symbol as temporal guard interval as illustrated in Figure 2. As shown in Figure 2, the basic signal format on the PHY layer is a RF burst started with a preamble that is followed by a payload data part. Five different types of PHY bursts are defined with different burst preamble formats to distinguish between each other: Broadcast Burst, Downlink Burst, Uplink Burst with Short Preamble, Uplink Burst with Long Preamble and Direct Mode Burst.

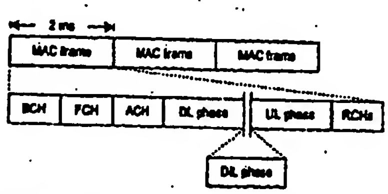

Figure 3: MAC frame structure for HIPERLAN/2.

The Data Link Control layer constitutes the logical link between AP and MTs. The functional entities in DLC layer are Medium Access Control function, Error Control function and Radio Link Control function. In HIPERLAN/2, the MAC protocol is based upon a dynamic TDMA/TDD scheme with centralized control. The Basic MAC frame structure is shown in Figure 3. The duration of each MAC frame is 2ms. Each MAC frame consists of transport channels BCH (Broadcast Channel), FCH (Frame Channel), ACH (Access Feedback Channel), a DL (Down-Link) and UL (Up-Link) phase, and one or many RCHs (Random Channel). A DiL (Direct Link) phase is also contained between DL phase and UL phase if Direct Mode is used. The duration of the BCH is fixed while the duration of the FCH, DL phase, DiL phase, UL phase and the number of RCHs are dynamically adapted by the AP according to the current traffic condition. The BCH (downlink only) contains control information that reaches all the MTs. It provides information about transmission power levels, starting point and length of the FCH and RCH, wake-up indicator, and identifiers for identifying both the HIPERLAN/2 network and the AP. The FCH (downlink only) contains an exact description of how the DL phase, UL phase and RCH are configured in the current MAC frame. The ACH (downlink only) contains information on previous access attempts made in the RCH. The DL and UL phase (bi-directional) is for the traffic of PDU (Protocol Data Unit) trains to and from the MTs respectively. The RCH (uplink only) is used by the MTs to request transmission resources for the DL or UL phase in upcoming MAC frames, and to convey some RLC signaling messages. Collisions may occur in RCH and the results from RCH access will be reported to MTs in ACH.

τ_{10} and τ_{20} are transmission delays from AP to MT, GRP1 and GRP2 respectively. In this method, after the request for geolocation services is initiated by MT or GCS, AP assigns the optional DiL phase in the current MAC frame to the MT and the MT transmits a Direct Mode Burst within the DiL phase. Then GRP measures the receiving time of the Direct Mode Burst from the MT. The TOAs from AP to GRPs τ_{10} and τ_{20} can be accurately estimated at GCS since the distances between each GRP and AP are known. Consequently, the TDOA from MT to GRP1 and GRP2 can be calculated as follows:

$$\begin{aligned} TDOA_{21} &= \tau_2 - \tau_1 \\ &= [(\tau_{20} + \tau_{21}) - (\tau_{00} + \tau_{01})] \\ &\quad - [(\tau_{10} + \tau_{11}) - (\tau_{00} + \tau_{01})] \\ &= (\tau_{20} + \tau_{21}) - (\tau_{10} + \tau_{11}) \end{aligned} \tag{2}$$

Using this method, GCS acts as a master that collects measurements of receiving time of Direct Mode Burst from multiple GRPs and calculates TDOAs as well as estimating position of MT basing on TDOAs. As a result, after measuring receiving time of Direct Mode Burst, GRPs have to request a UL phase to report the measurement to GCS. Using the GRP-based TDOA method, only one AP is needed to perform geolocation function and no forced handoff between APs are needed.

IV. BURST SYNCHRONIZATION METHODS IN HIPERLAN/2 OFDM SYSTEMS

Using the geolocation methods discussed in the preceding section, we need to determine the receiving time of physical layer burst signals at MT and AP (or GRP) that is also known as symbol timing synchronization. Symbol timing for OFDM signals is very different from that of a single carrier signals because no eye-opening point, which is the best sampling time, can be found [6]. In this section, we present burst synchronization methods in HIPERLAN/2 OFDM systems that can be used for geolocation purpose.

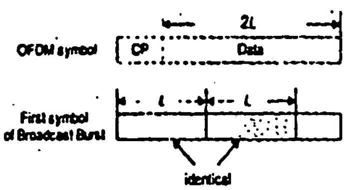

Figure 6: Training symbol in HIPERLAN/2 burst preamble.

In burst transmission mode, receiver must continuously scan for incoming data and the symbol synchronization time is required to be as short as possible. In HIPERLAN/2, the burst preamble consists of special training symbols that are used to accomplish the timing synchronization and frequency offset correction within the duration of several OFDM symbols. The first symbol in the Broadcast Burst preamble consists of two identical parts in the time domain as illustrated in Figure 6. The timing synchronization can be performed by searching for the training symbol with two identical halves. A timing metric M is formed by performing sliding correlation of two consecutive parts of the received signal $r(k)$ (each of which has a length of L) as follows [6]:

$$M(d) = \frac{|P(d)|^2}{[R(d)]^2}, \tag{3}$$

where

$$\begin{aligned} P(d) &= \sum_{m=0}^{L-1} r^*(d+m) \cdot r(d+m+L) \\ R(d) &= \sum_{m=0}^{L-1} |r(d+m+L)|^2 \end{aligned} \tag{4}$$

and * denotes complex conjugate operation. Figure 7 shows the timing metric output of the sliding correlation described above where the first vertical line indicates the starting point of the first symbol and the last vertical line is the starting point of the second symbol. Our simulation results show that this timing synchronization method works well in AWGN channel and an exponential channel that will be described in the next section. Statistical results of the timing metric obtained from our simulations (which are omitted here due to lack of space) also closely match the theoretical results presented in [6].

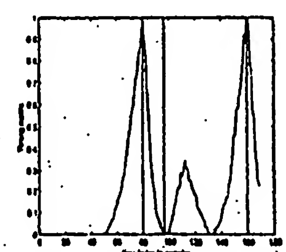

Figure 7: Timing metric without noise.

V. SIMULATION RESULTS

To study the performance of geolocation systems, ranging accuracy must be obtained first. Then the ranging accuracy can be mapped into positioning accuracy by simulations or by statistical methods. We obtained statistical results of timing errors from computer simulations using the timing synchronization method presented in the preceding section. Parameters for computer simulations are summarized in Table 1. A raised-cosine lowpass filter is used to take account of band-limitation condition that has impacts on the accuracy of timing synchronization. At the receiver an up-sampling rate of 10 is used, which is needed to make adequately high resolution in delay/distance estimation.

Two channel models are used in our simulations, AWGN channel and frequency selective channel with an exponential power delay profiles as described in [6]. AWGN channel is used to show the performance in a benign channel while the exponential channel represents a more realistic environment. For the frequency selective channel, 5 paths are chosen with path delays of 0, 2, 4, 6, and 8 samples, where sampling rate is 20MHz, so that the channel impulse response is shorter than the guard interval. The amplitude of each path is calculated from the exponential distribution:

$$A_i = \exp(-\tau_i / 8) \qquad (5)$$

where A_i is the amplitude of the ith path and τ_i is the delay of the ith path in samples. The phase of each path is chosen from a uniform distribution from 0 to 2π.

Table 1: Parameter values for HIPERLAN/2 OFDM transceiver simulations.

PARAMETER	VALUE
Number of OFDM sub-carriers	52
Sub-carrier frequency spacing	0.3125 MHz
Sampling rate	20MHz
Samples per symbol	80
Samples in cyclic prefix	16
Raised-cosine lowpass filter	$T = 1/(20\text{MHz}), \alpha = 0.25$
Up-sampling rate at receiver	10

Figure 8 shows simulation results of timing errors for the two aforementioned channel models. We can observe that compared to the AWGN channel, the mean and standard deviation of timing errors became worse for exponential channel. Since the sampling period at the receiver is $T_s = 5\text{ns}$ (with up-sampling rate 10), one sample timing error maps to 1.5m ranging error. As a result, the mean of ranging errors remains around 3m for AWGN channel and 7.5m for exponential channel when signal-to-noise ratio is greater than 9dB. The timing synchronization method used in our simulations is pretty simple since only one OFDM training symbol is used. Some other timing methods are needed to further improve the accuracy in real multi-path indoor environment.

VI. CONCLUSIONS

In this paper we presented indoor geolocation methods and system architectures for HIPERLAN/2 wireless LANs. A novel method is proposed to measure TOA and TDOA from OFDM signal by exploiting MAC frame structure in HIPERLAN/2 wireless LANs. A symbol timing synchronization method is used to obtain the statistical results of timing errors that were mapped into ranging accuracies. The simple timing method used in this paper can result in a mean ranging errors around 7.5m in the exponential channel. Other timing methods have to be combined to further improve the performance.

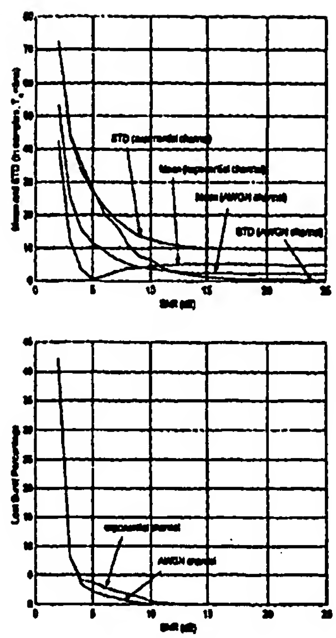

Figure 8: Mean and STD (standard deviation) of timing errors for AWGN and exponential channels.

ACKNOWLEDGEMENT

The authors would like to express their appreciation to TEKES, Nokia, and Finnish Defense Forces for supporting most parts of this project. We also thank Dr. Jacques Beneat, our colleague at CWINS, for fruitful discussions and a variety of help.

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[redacted]

Positioning Using the ATSC Digital Television Signal

Dr. Matthew Rabinowitz, Dr. James Spilker
Rosum Corporation Whitepaper

I Overview

The technique discussed herein may be used to position cell-phones, PDAs, pagers, cars, OCDMA transmitters and a host of other devices. We make use of a signal which has excellent coverage over the United States, and the existence of which is mandated by the Federal Communication Commission. This technique requires no changes to the Digital Broadcast Stations. In order to accommodate robust indoor positioning, the signal we use has a power advantage over GPS of more than 40dB, and substantially superior geometry to that which a satellite system could provide. In order to minimize the effects of multipath, the signal has roughly six times the bandwidth of GPS. In addition, unlike GPS, the signal is not affected by transmitter Doppler or ionospheric propigation delays. Due to the high power and low duty factor of the DTV signal used for ranging, the processing requirements are minimal. The positioning technique accommodates far cheaper, lower speed, and lower power devices than a GPS technique would require. Unlike the terrestrial Angle-of-Arrival, Time-of-Arrival, and Enhanced-Time-Difference-of-Arrival positioning systems for cell-phones, this technique requires no change to the hardware of the cellular base station, and can achieve positioning accuracies on the order of 1 meter. When used to position cell-phones, the technique is independent of the air-interface, whether GSM or CDMA. A wide range of UHF frequencies has been allocated to DTV transmitters. Consequently, there is redundancy built into the system to protect against deep fades on particular frequencies due to absorption, multipath and other attenuating effects. In overview, the technology exploits the considerable Digital TV infrastructure to position wireless devices more effectively and far more economically than any current alternative.

II DTV Roll-out and Coverage

Digital Television was first implemented in the United States in 1998. As of the end of 2000, 167 stations were on the air broadcasting the DTV signal. As of February 28 2001, 1266 DTV construction permits had been acted on by the FCC commission. According the Federal Communication Commission's objective, all television transmission will soon be digital, and analog signals will be eliminated. Public broadcasting stations must be digital by May 1 2002 in order to retain their licenses. Private stations must be digital by May 1 2003. A total of over 1600 DTV stations are expected in the United States. The signal structure used for DTV is specified by the American Television Standard Committee (ATSC). Herein, we describe how the DTV signal can be used for location capability throughout the Continental United States. We describe results of tests performed in tracking the DTV signal indoors. The coverage and geometry provided by DTV stations over the Continental US (CONUS) are analyzed herein.

III Signal Description for Digital TV

The ATSC signal uses 8-ary Vestigial Sideband Modulation (8VSB). The symbol rate of the ATSC signal is f_s = 10.762237MHz which is derived from a 27.000000MHz clock. The ATSC frame appears as in Figure 1. The frame consists of a total of 626 segments, each with 832 symbols, or a total of 520832 symbols. There are two field synchronization segments in each frame, and each segment has 4

symbols used for synchronization purposes. The structure of the synchronization segment is shown in Figure 2. Notice that the two synchronization segments in a frame differ only to the extent that the middle set of 63 symbols are inverted in the second frame. The structure of the data segment is illustrated in Figure 3. Notice that the first four symbols, which are {-1, 1, 1, -1} are used for segment synchronization; the other 828 symbols carry data. Since the modulation scheme is 8-ary VSB, each symbol carries 3 bits of coded data. A rate 2/3 coding scheme is used.

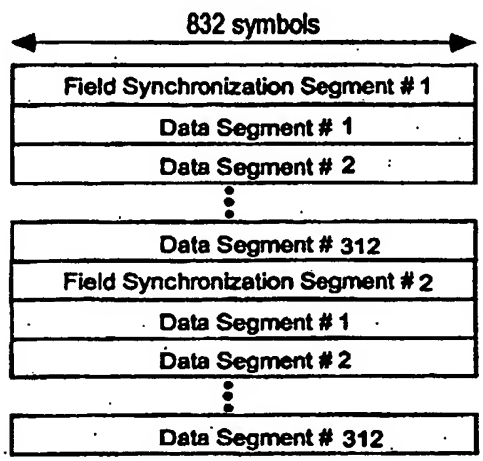

Figure 1 DTV Data Frame

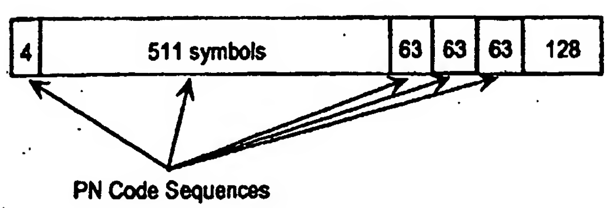

Figure 2 DTV Synchronization Segment in the ATSC Frame

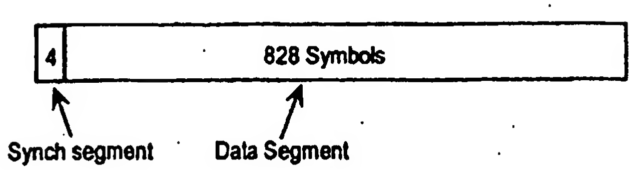

Figure 3 DTV Data Segment in the ATSC frame

The 8VSB signal is constructed by filtering. The in-phase segment of the symbol pulse has a raised-cosine characteristic [3]. The pulse can be described as:

$$p(t) = sinc\left(\frac{\pi t}{T}\right)\frac{\cos\left(\frac{\pi\beta t}{T}\right)}{1-\frac{4\beta^2 t^2}{T^2}} \tag{1}$$

Where $\beta = 0.05762$. This signal has a frequency characteristic:

$$P(f) = \begin{cases} T & ;0 \le |f| < \frac{1-\beta}{2T} \\ \frac{T}{2}\left\{1+\cos\left[\frac{\pi T}{\beta}\left(|f|-\frac{1-\beta}{2T}\right)\right]\right\}; & \frac{1-\beta}{2T} \le |f| \le \frac{1+\beta}{2T} \\ 0 & ;|f| > \frac{1+\beta}{2T} \end{cases} \tag{2}$$

From which we see that the one-sided bandwidth of the signal is $(1+\beta) = 5.38\text{MHz} + 0.31\text{MHz}$. In order to create a VSB signal from this in-phase pulse, the signal is filtered so that only a small portion of the lower sideband remains. This filtering can be described as:

$$P_v(f) = P(f)(U(f) - H_\alpha(f)) \tag{3}$$

$$U(f) = \begin{Bmatrix} 1, f \ge 0 \\ 0, f < 0 \end{Bmatrix} \tag{4}$$

where $H_\alpha(f)$ is a filter designed to leave a *vestigial* remainder of the lower sideband. A plot of the gain function for $H_\alpha(f)$ is shown in Figure 4.. The filter satisfies the characteristics:
$H_\alpha(-f) = -H_\alpha(f)$ and $H_\alpha(f) = 0, f > \alpha$

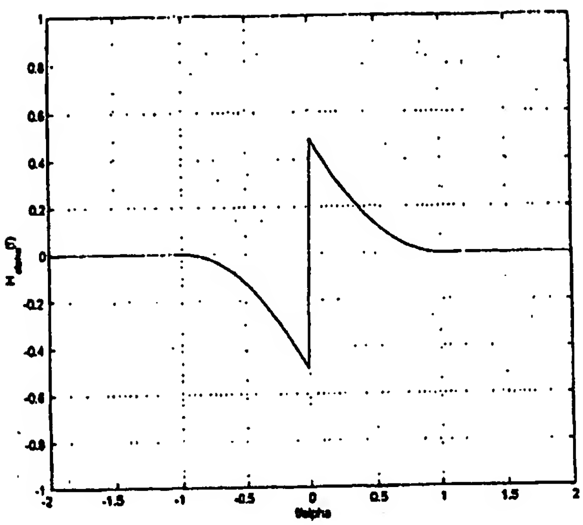

Figure 4 Transfer function of the filter H_α

The response $U(f)P(f)$ can be represented as

$$U(f)P(f) = \frac{1}{2}(P(f) + j\breve{P}(f)) \tag{5}$$

Where $\breve{P}(f) = -j\,\mathrm{sgn}(f)P(f)$ is the Hilbert transform of $P(f)$. The VSB pulse may be represented as

$$P_v(f) = \frac{1}{2}X(f) + \frac{j}{2}(\breve{X}(f) + 2X(f)H_\alpha(f)) \tag{6}$$

and the baseband pulse signal

$$p_v(t) = \frac{1}{2}x(t) + \frac{j}{2}(\breve{x}(t) + x_\alpha(t)) = p_{vi}(t) + jp_{vq}(t) \tag{7}$$

where $p_{vi}(t)$ is the in-phase component, $p_{vq}(t)$ is the quadrature component, and

$$x_\alpha(t) = 2\int_{-\infty}^{\infty} X(f)H_\alpha(f)e^{j2\pi ft}df \tag{8}$$

Before the data is transmitted, the ATSC signal also embeds a carrier signal, which has -11.5dB less power than the data signal. This carrier aids in coherent demodulation of the signal. Consequently, the transmitted signal can be represented as:

$$s(t)=\sum_{n}C_n\{p_{vi}(t-nT)\cos(\omega t)-p_{vq}(t-nT)\sin(\omega t)\}+A\sin(\omega t) \quad (9)$$

Where C_n is the 8-level data signal.

IV Tracking the DTV Signal

We will discuss three different techniques of tracking the DTV signal. It should be realized that many other techniques exist for tracking the DTV signal; however, we describe only some of the canonical approaches herein. Further discussion of the some standard tracking techniques is provided in [1] and [2]. We do not describe herein how the receiver architecture can be optimized for the structure of DTV synchronization signals, since that is overly detailed for the scope of this white paper. Suffice to say, if all processing is implemented in firmware, the duration of a pseudorange measurement for one DTV channel has an expected value of 23ms on a low-power, low-cost off-the-shelf DSP.

IV. A Software Receiver

The most thorough approach to mitigating the effects of multipath is to sample an entire autocorrelation function, rather than to use only early and late samples as in a hardware setup. In the case that position can be computed with a brief delay, such as in E911 applications, the simplest approach is to use a *software receiver*, which samples a sequence of the filtered signal, and then processes this in firmware on a DSP. Figure 5 displays a typical architecture for tracking in software. The phase-locked loop implements a narrowband filter to extract the carrier from the signal. The signal is then downconverted by mixing with the carrier signal; the baseband signal is emitted from the filter. The receiver can also be implemented with multiple downconversions for ease of implementing the noise filters. In addition, the receiver need not downconvert the signal to baseband before sampling. Downconversion may be implemented by undersampling the bandpass filtered signal.

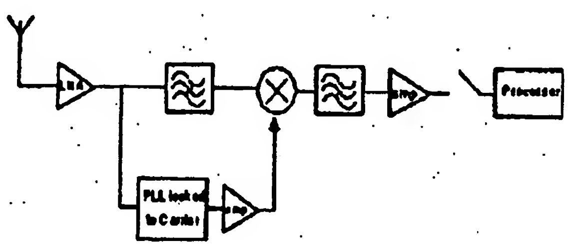

Figure 5: Architecture for the Software Receiver

We will describe here a software receiver approach that assumes nominal offset frequency for the downconverted sampled signal. For the method of Figure 5 where the signal is converted directly to baseband, the nominal offset is 0Hz. This algorithm describes how the complete autocorrelation function can be generated, in a software receiver, based on samples of a signal $s(t)$. This algorithm may be implemented far more efficiently for the low duty factor signal. Let T_i be the period of data sampled, ω_{in} be the nominal offset of the sampled incident signal, and let ω_{offset} be the largest possible offset frequency, due to Doppler shift and oscillator frequency drift.

- $R_{max} = 0$
- Create a complex code signal

$$s_{code}(t) = \sum \overline{C}_n \{p_{ni}(t-nT) + jp_{nq}(t-nT)\}$$

where $\overline{C}_n$ is zero for all symbols corresponding to data signals and non-zero for all symbols corresponding to synchronization signals.

- For $\omega = \omega_{in} - \omega_{offset}$ to $\omega_{in} + \omega_{offset}$ step $0.5\frac{\pi}{T_i}$
  - Create a complex mixing signal

    $s_{mix}(t) = \cos(\omega t) + j\sin(\omega t), t = [0..T_i]$
  - Combine the incident signal $s(t)$ and the mixing signal $s_{mix}(t)$

    $s_{comb}(t) = s(t)s_{mix}(t)$
  - Compute the correlation function $R(\tau) = s_{code} * s_{comb}(\tau)$
  - If $\max_\tau |R(\tau)| > R_{max}$,

    $R_{max} \leftarrow \max_\tau |R(\tau)|, R_{store}(\tau) = R(\tau)$
- Next ω

Upon exit from the process, $R_{store}(\tau)$ will store the correlation between the incident signal $s(t)$ and the complex code signal $s_{code}(t)$. $R_{store}(\tau)$ may be further refined by searching over smaller steps of ω. The initial step size for ω must be less than half the Nyquist rate $\frac{2\pi}{T_i}$.

IV. B Hardware Receiver

Figure 6 displays the architecture for a Maximum Likelihood (ML) receiver that may be implemented in hardware. This receiver employs a decision-directed architecture. Namely, the actual data symbols $\{C_n\}$ must be determined in the receiver, or must be known a-priori, as in the case of the ATSC synchronization codes. It should be understood that many different versions of, and approximations to, this architecture may be implemented without changing the essential idea. We assume, as above, that the receiver first locks onto the injected carrier signal for coherent modulation. This is not necessary; receivers can be implemented which simultaneously determine symbol synchronization and carrier phase [3]. The signal is coherently downconverted to produce both an in-phase and quadrature component. These components are then passed through a matched filter, which are respectively the in-phase and quadrature symbols reversed in time. The signal is then differentiated, and sampled at the times $nT + \hat{\tau}$ where $\hat{\tau}$ is the current estimate of the time offset necessary for synchronization. The sampled signal is then mixed with the known data sequence $\{\overline{C}_n\}$ Since the Phase-Locked-Loop (PLL) bandwidths required for navigation are small compared with those required for DTV reception, we do not assume demodulation and detection of the DTV data symbols. Consequently, as discussed above, $\{\overline{C}_n\}$ is 0 except where the symbol corresponds to a known synchronization symbol. The in-phase and quadrature samples are then input to the summation filters. If $\hat{\tau}$ is the ML estimate, then the outputs of the summations should be 0. The purpose of the control loop is to drive the outputs of the summation devices to 0. The control law combines the in-phase and quadrature outputs, and may also filter the information, to drive the NCO so that the outputs of the summation devices go to 0. The summation devices will sum over a number of symbols consistent with the update rate of the loop. The NCO also drives the code generator, so that th cod symbols $\overline{C}_n$ are aligned with the incident signal.

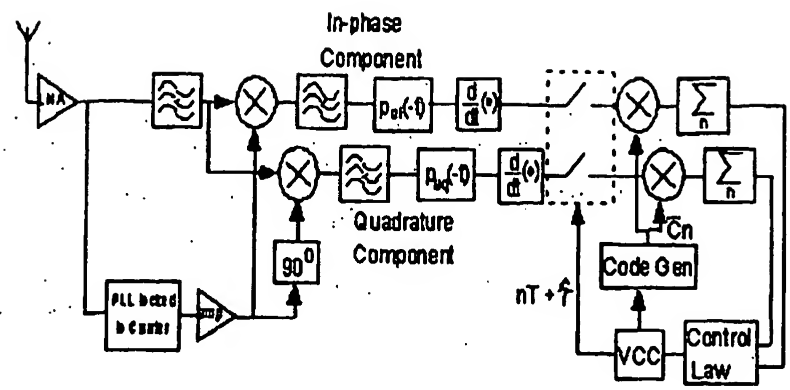

Figure 6: Architecture for a ML Decision-Directed Receiver

There are many other ways of implemented hardware code tracking and synchronization [4] such as with the use of Early-Minus-Late Power Discriminators, Dot-Product Discriminators, and the Coherent Early-Minus Late Discriminator.

While we have only discussed the tracking mode of the receiver, another mode is required for signal acquisition. In the case of the DTV signal, the initial acquisition search can be broken into two parts. The first is a search for the 4 synchronization symbols on each data segment, or a search over 832 chips. This is followed by a search for the Field-Synch Segment, or a search over 313 chips (if the middle 63-chip PN sequence is ignored). This can be achieved very quickly. In addition, while this receiver makes use of both in-phase and quadrature symbols, simpler techniques may make use of only the in-phase or quadrature components. Such techniques may have desirable properties for multipath rejection.

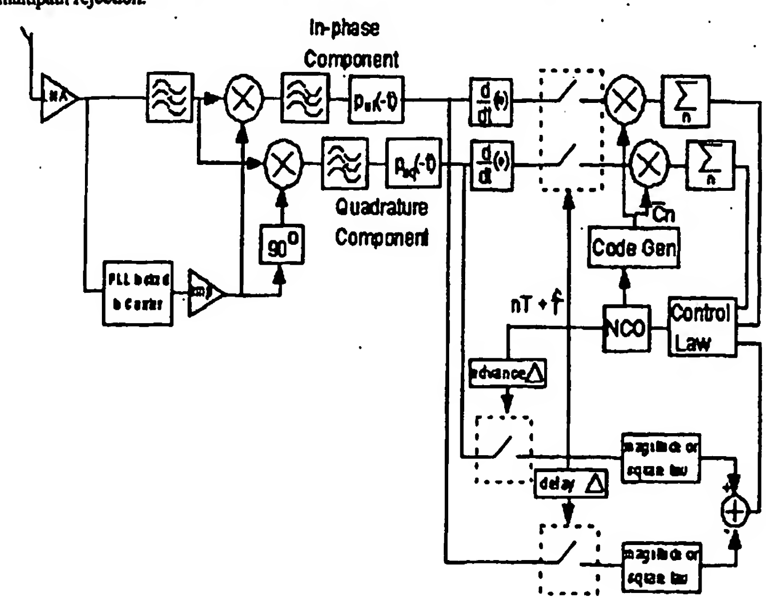

Figure 7: Architecture for a Decision Directed Receiver Combined with a Non-Decision-Directed Receiver

The receivers described above only use the synchronization chips in order to update the estimate $\hat{\tau}$. However, there are other techniques which may be used for resolving $\hat{\tau}$ using the data symbols as well as the synchronization symbols, in a non-decision directed architecture. Such a method is illustrated in figure 7. Note that this technique combines the correlator technique, which only makes use of the synchronization symbols, with a non-decision-directed approach that uses an early-late gate synchronizer. The latter can also update $\hat{\tau}$ based on the data symbols, since it doesn't require knowledge of the symbols to implement the tracking loop. The control law would combine the inputs from the coherent and non-coherent detectors, roughly in inverse proportion to the standard deviation of the timing error from each tracking loop. Of course, additional filtering can be applied to enhance tracking loop performance.

V The Navigation System

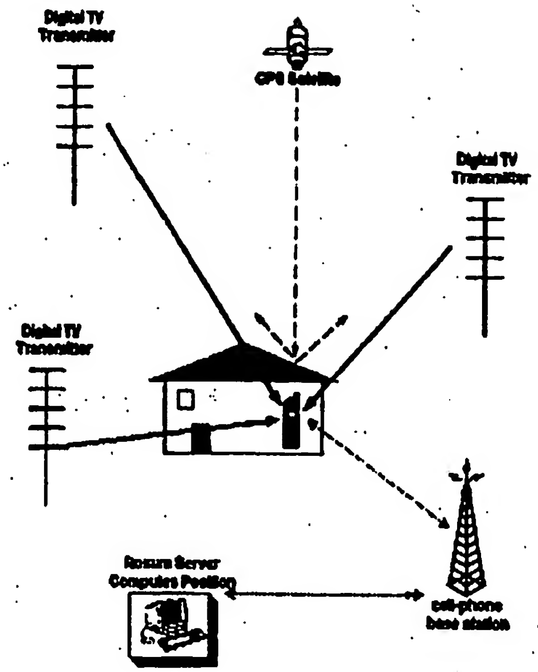

Figure 8: Architecture for positioning Digital TV transmitters

An overview of the navigation system architecture is illustrated in Figure 8. The position calculation may be implemented at the UT, or at a Processor associated with the cellular base station. Unlike the case of a satellite-based positioning technique, the location of the transmitters is unchanging, and need not be continually updated. This DTV transmitter location data may be stored at the UT or the cellular based station. By one of a variety of tracking techniques, the UT measures the pseudorange to each of the visible transmitters. Pseodoranges to three transmitters is sufficient to resolve the user's latitude, longitude, and clock bias, with sufficient accuracy to substantially exceed the FCC's phase II E911 requirements for position determination. Latitude and longitude may also be combined with an altitude map to refine the position computation. In order to compute an accurate location of the UT, the timing of the DTV synchronization code transmissions must be known.

Monitor units at known positions may be used to independently monitor the DTV station clock correction. These may be applied to the position computation at the Rosum server, or they may be transmitted to the UT for position computation. For the architecture shown, this information is maintained at the Rosum server. Alternatively, the DTV transmitters may broadcast to the UT their own clock correction, as is done for GPS satellites. Due to adjacent NTSC broadcast channels, the ATSC specification requires DTV broadcasts to be stable within 3 Hertz. To meet this requirement, most DTV broadcasts are synchronized to GPS or other stable clocks. Consequently, the DTV timing information may be updated less than once per hour, for a meter-lev l positioning syst m.

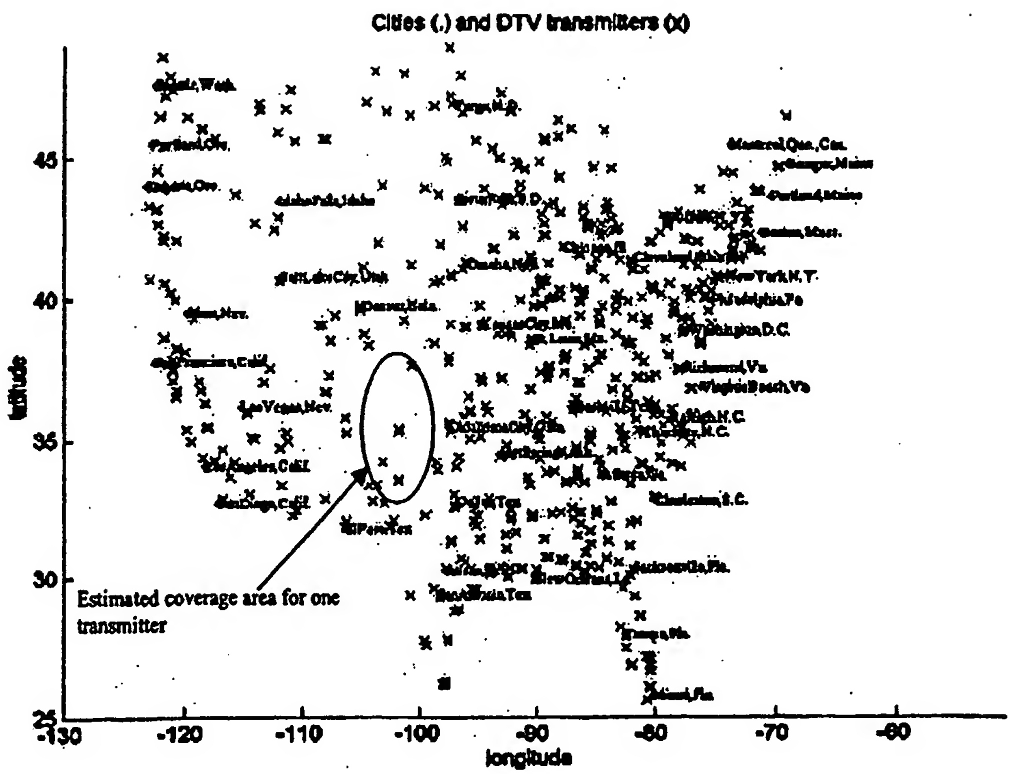

Figure 9: Locations of the first 1038 transmitters. The ring indicates the approximate coverage area of the ranging signal for one transmitter, assuming propagation according to CCIR model.

The positioning accuracy which can be achieved using this technique is determined by the Dilution of Precision (DOP) arising from the arrangement of the visible transmitters around the user terminal. Studies were conducted to analyze system performance in non-urban areas, based on those stations which were either transmitting DTV signals, or were in the process of setting up DTV capability. As of April of 2001, that amounted to roughly 1032 DTV stations. The analysis was performed based on the CCIR propagation model for signals up to 1GHz, which is conservative. The model assumes a $\frac{1}{r^2}$ power rolloff for roughly 15km, followed by a $\frac{1}{r^{3.47}}$ rolloff to the effective horizon. $d = \sqrt{\frac{8Rh}{3}}$ where R is the Earth radius and h is the height of the transmitter; then a $\frac{1}{r^{9.54}}$ power rolloff thereafter. In addition to the path loss, the link analysis assumes a polarization loss of 3dB, a matching loss in the UT f 3dB, additional attenuation loss of 20dB, and a delay-locked loop bandwidth of 5Hz. The analysis also assumes that only the synchronization PN sequences are used for ranging, which causes a 23.7dB power loss since .43% of the transmitted symbols are for synchronization. An additional power gain is realized, however, since the synchronization symbols

are, on average, higher power then the data symbols. We also assume that a loop SNR of 10dB is necessary in order to achieve an accurate pseudorange.

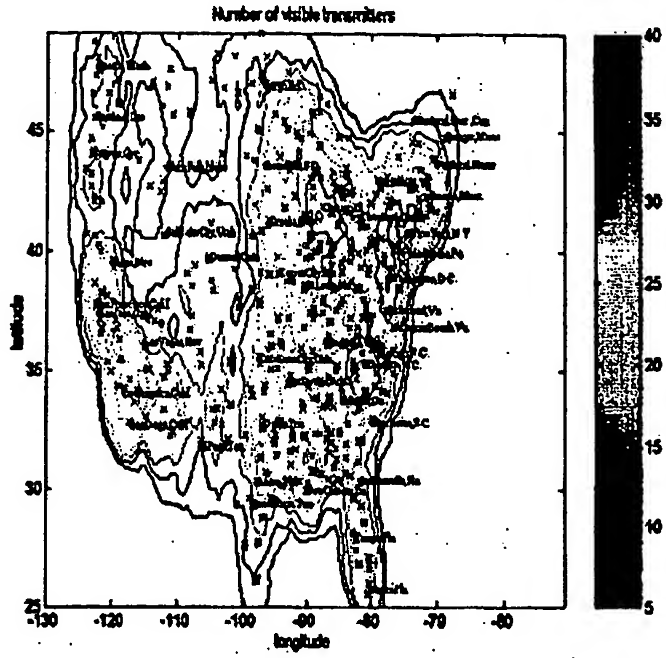

Figure 10: Contours of the number of visible UHF signals for first 1038 transmitters. Any channel for which the strongest and second-strongest signals are within 30dB of one another is dropped completely, and not used for navigation. Of course, this need not be the case.

Figure 9 displays the locations of the first 1032 DTV stations throughout the United States. Notice that the approximate coverage area of a single transmitter's ranging signal is substantially larger than the coverage area for DTV picture reception. This is due to processing gain, since precise positioning does not require reception of the DTV data. Figure 10 displays a contour map of the number of the number of transmitters visible over the CONUS, given the link assumptions discussed above. Figure 11 shows the achievable East DOP for the Continental US, for the available signals. Although multipath will dominate the noise equation, and this will vary with location, we may assume a pseudorange accuracy of roughly 1m, so the contours also roughly indicate the positioning accuracy in meters. Figure 12 illustrates the North DOP for the Continental US. Note that this DOP could be further enhanced if the clock bias of the UT is independently resolved using the cellular base stations; however, as can be clearly seen from the figures, this does not appear to be necessary.

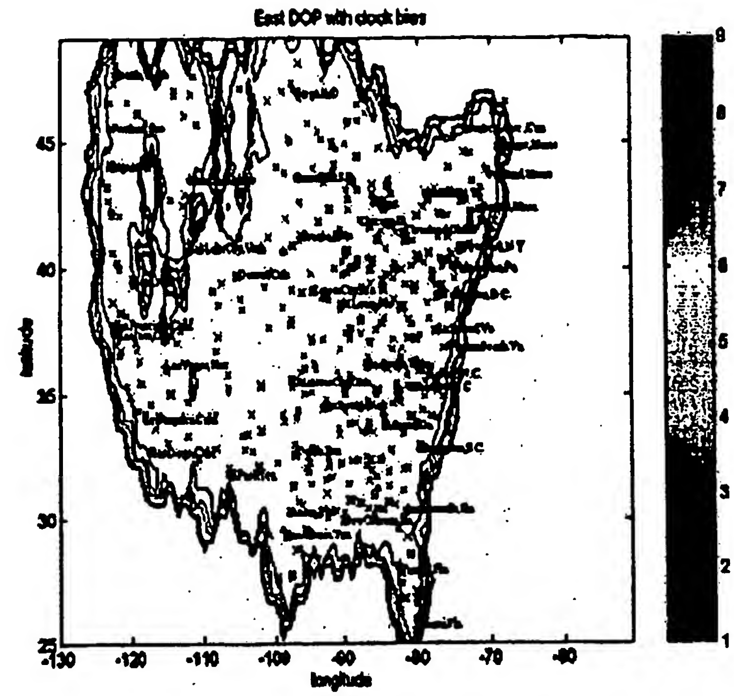

Figure 11: East DOP for the first 1038 transmitters, assuming the CCIR propagation model. Only UHF signals are used, and no channel sharing is allowed.

VI Experimental Results

A technique similar to that of section IV was applied to DTV transmissions arising from San Jose, California, received indoors in Palo Alto, California. Figure 13 displays an example spectrum for a 10 *ms* sample of the signal from KICU channel 52 DTV broadcast from San Jose. The signal is downconverted to center frequency of 27MHz, or digital frequency of 0.54. The signal was digitally bandpass filtered to a bandwidth of 6MHz. The computed autocorrelation function for the in-phase and quadrature component of this signal are illustrated in Figure 14. Note that this is the autocorrelation for only the 4 synchronization symbols at the beginning of each segment. The characteristics of the signal are highlighted by figure 15. This figure displays a portion of the autocorrelation peak for the in-phase channel. From the smoothness of the curve, one can see that the signal-to-noise ratio is high. In addition, the curvature of the peak indicates the high signal bandwidth which makes this signal robust to multipath. The combination of wide signal bandwidth, high signal power, and simple signal processing result in a positioning technology more effective than any of the alternatives.

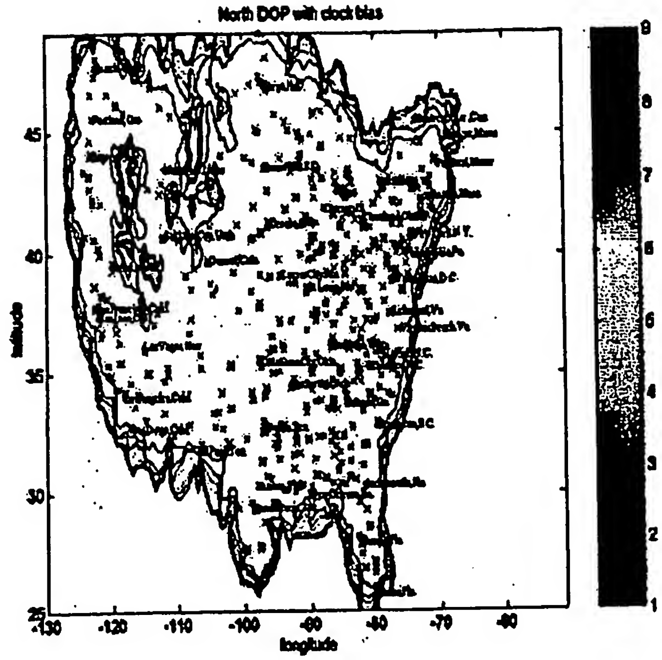

Figure 12: North DOP for the first 1038 transmitters, assuming the CCIR propagation model. Only UHF signals are used, and no channel sharing is allowed.)

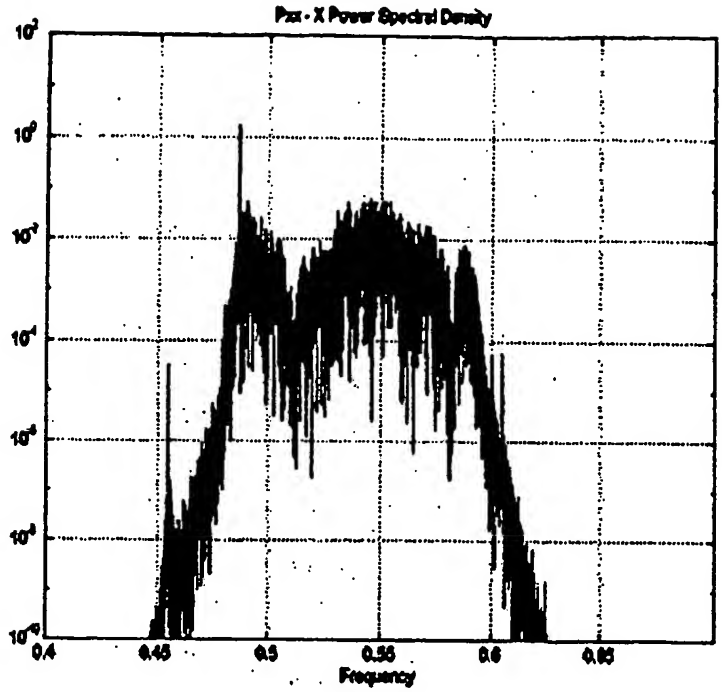

Figure 13: Spectrum of the KICU channel 52 signal after 6MHz digital bandpass filtering